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BNL-77121-2006-JA

BIASED CLOUD RADIATIVE FORCING DUE TO SPECTRAL DISPERSION

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Submitted to
Science

October 2006

Environmental Sciences Department/Atmospheric Sciences Division

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Biased Cloud Radiative Forcing due to Spectral Dispersion

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Cloud parameterization is key to accurately modeling the Earth's climate and climate change. Here we show that relative dispersion (ε, ratio of the standard deviation to the mean radius) of the cloud droplet size distribution, whose effect on cloud radiative properties has not been adequately represented in even state-of-the-art climate models, can lead to a bias in global mean shortwave cloud radiative forcing (CRF, the shortwave (solar) radiative flux when clouds are present minus that when clouds are absent) of -1 Wm^{-2} to -10 Wm^{-2}, which is comparable to the warming caused by doubled CO_2. This finding points to a microphysical reason for the overestimation of cloud radiative cooling by climate modes compared to satellite observations (1).

In state-of-the-art climate models, cloud radiative properties are represented in terms of effective radius (2, 3), which is further parameterized as (4, 5)

$$r_e = \beta[3/(4\pi\rho)L/N]^{1/3}, \qquad (1)$$

where ρ is the water density, r_e is the effective radius, L is the cloud liquid water content, and N is the droplet concentration. A constant value of β (e.g., β =1) has been generally assumed in climate models. However, compelling evidence has indicated that β depends on the spectral shape of the cloud droplet size distribution, and the dependence can be well described by (4, 5)

$$\beta = (1+2\varepsilon^2)^{2/3} / (1+\varepsilon^2)^{1/3}. \qquad (2)$$

Prepared as a Brevia for Science, Oct. 10, 2006
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Through β, any change in ε will alter the effective radius, and hence cloud radiative properties such as cloud-top albedo (R) and CRF. If all other cloud properties are the same, an ambient cloud with $\varepsilon > 0$ exhibits a larger effective radius and hence smaller cloud albedo compared to the corresponding monodisperse cloud with $\varepsilon = 0$ [hence $\beta = 1$ according to Eq. (2)], with the difference given by (see Supporting online Text)

$$\Delta R = R - R_0 = R_0 \, [(1-\beta)(1- R_0)]/[\, R_0+\beta(1- R_0)], \qquad (3)$$

where R_0 denotes the cloud-top albedo for the corresponding monodisperse cloud. According to Ref. (6), this difference in R will lead to an error in the global mean shortwave CRF given by

$$\Delta F = - 0.8/4SAR_0 \, [(\beta - 1)(1- R_0)]/[\, R_0+\beta(1- R_0)] \qquad (4)$$

where S, and A are the solar constant and the fraction of the globe covered by marine stratiform clouds, respectively. The minus sign indicates that the common assumption of the monodisperse cloud overestimates the cloud radiative cooling.

Equations (4), (3), and (2)) permit calculation of the dependence of the errors in R and CRF on ε at different values of R_0 (Fig. 1). It is evident that the errors in R and CRF increases with increasing ε, and are most sensitive to ε in the neighborhood of R_0 = 0.5 ~ 0.6, which is near the cloud albedo typically observed in stratiform clouds and corresponds to the maximum Twomey effect (6). Moreover, observational studies have shown that ε varies from 0 to 1 in ambient clouds (4, 5). From Fig. 1, this variation in ε leads to errors in CRF ranging from -1 to -10 Wm^{-2}, which is comparable to the climate forcing caused by doubling CO_2 in magnitude, but opposite in sign. Comparison studies have revealed that cloud radiative cooling effects in major climate models are much larger than that inferred from satellite observations (1). The ε-induced bias in CRF may be responsible for part of this model-observation discrepancies.

Since the seminal 1974 work by Hansen and Travis (2), ε has been considered to be marginal importance to cloud radiative properties compared to effective radius. However, the above analysis demonstrates that through the dependence of effective radius on ε alone, ε can exert a climatic impact comparable to that induced by doubled CO_2. Moreover, spectral shape of the cloud droplet size distribution also has strong impact on hydrological processes such as precipitation. The overall impact of ε on climate simulations could be even larger because of the intimate relationships between radiative and hydrological properties. A through evaluation of the combined ε effects requires accounting explicitly for ε in climate models, bringing the issue of cloud-climate interactions to the heart of cloud physics.

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Supporting Online Material
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Derivation of Equations (3) and (4)

This work is supported by Department of Energy (DOE) grant DE-AC02-98CH10886.

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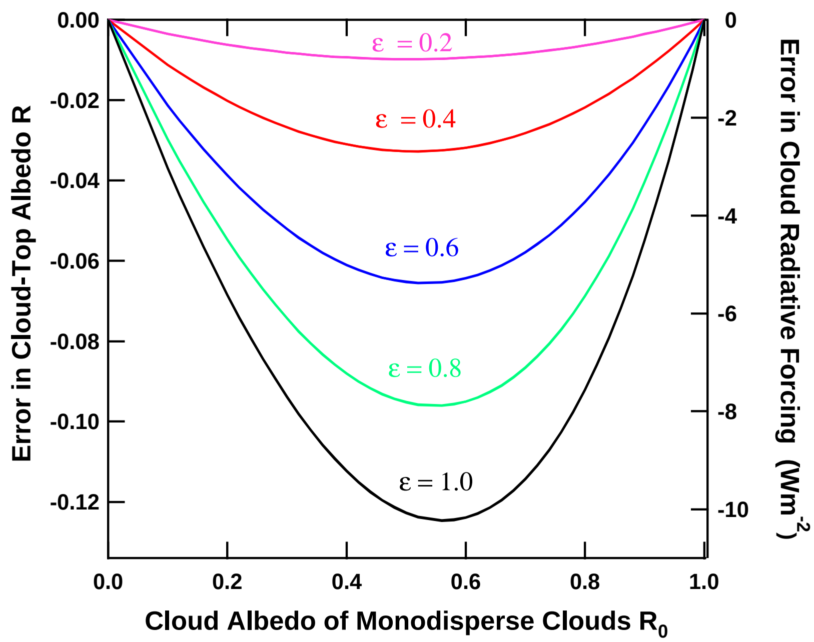

Figure 1. Errors in the cloud-top albedo and global mean cloud radiative forcing (CRF) as a function of the cloud-top albedo for the monodisperse cloud (R_0) at different values of the relative dispersion (ε). In the calculation, the values of the global mean fraction of low stratiform clouds (A), and the solar constant (S_0) were set to the same values as used in Ref. (9), i.e., A = 0.3, and S_0 = 1370 Wm^{-2}.

Supporting Online Material

Derivation of Equations (3) and (4)

Effective radius is parameterized as

$$r_e = \left(\frac{3}{4\pi\rho_w}\right)^{1/3} \beta \left(\frac{L}{N}\right)^{1/3}, \qquad \text{(S1)}$$

where ρ_w is the water density; L is the liquid water content; β is a dimensionless quantity. The cloud optical depth τ is related to r_e by

$$\tau = \frac{3H}{2\rho_w}\frac{L}{r_e}, \qquad \text{(S2)}$$

where H is the cloud thickness**.** Under the two-stream approximation of a nonabsorbing, homogenous, plane-parallel cloud, the cloud albedo R is given by (S1)

$$R = \frac{(1-g)\tau}{2+(1-g)\tau}, \qquad \text{(S3)}$$

where g is the asymmetry parameter and is considered constant. Combination of the above three equations, along with the assumption that all cloud properties but ε are the same for the real and corresponding monodisperse clouds, yields

$$R - R_0 = -\frac{(\beta-1)(1-R_0)R_0}{R_o + (1-R_0)\beta}, \qquad \text{(S4)}$$

where R_0 is the cloud albedo for the corresponding monodisperse cloud.

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